Recent Progress in (General) Gauge Mediation

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Questions for the LHC

- Where is the Higgs?
- What is the next layer of fundamental matter?
- What is the origin of the weak scale?
- Is naturalness a valid physical principle?
- What is the dark matter?

Supersymmetry?

Real-world SUSY-breaking

- Superpartners not observed => SUSY must be broken in the real world
- SUSY-breaking in the MSSM is explicit and must be soft (dimensionful) in order to not re-introduce quadratic divergences.
- Naturalness: expect typical size of soft masses around Mz, i.e. 100-1000 GeV

$$\mathcal{L}_{soft} = -\frac{1}{2}\sum_{i=1}^{3} M_i \lambda_i \lambda_i - \sum_{\tilde{f}=\tilde{Q},\tilde{u},\tilde{d},\tilde{L},\tilde{e}} \tilde{f}^\dagger m^2_{\tilde{f}} \tilde{f} + (Higgs)$$

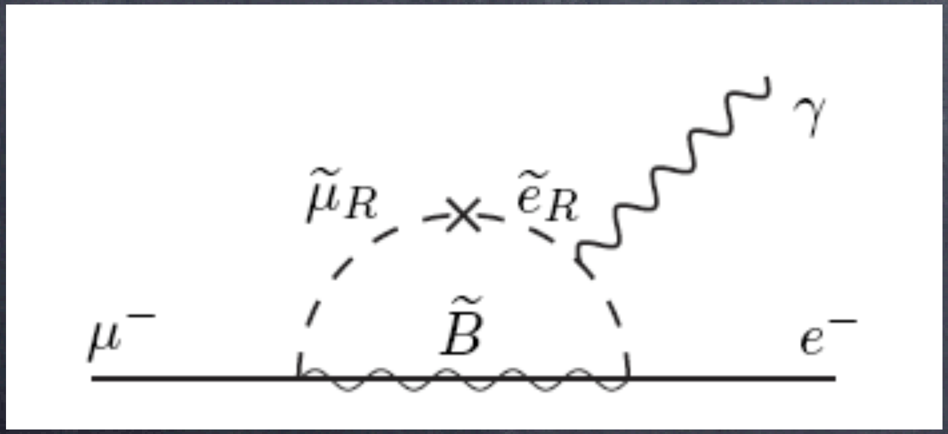
complex gaugino masses

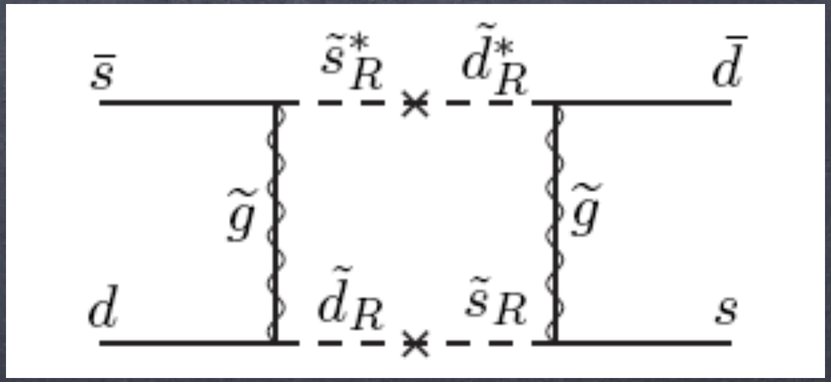
3x3 Hermitian squark and slepton masses

mu, B, A-terms

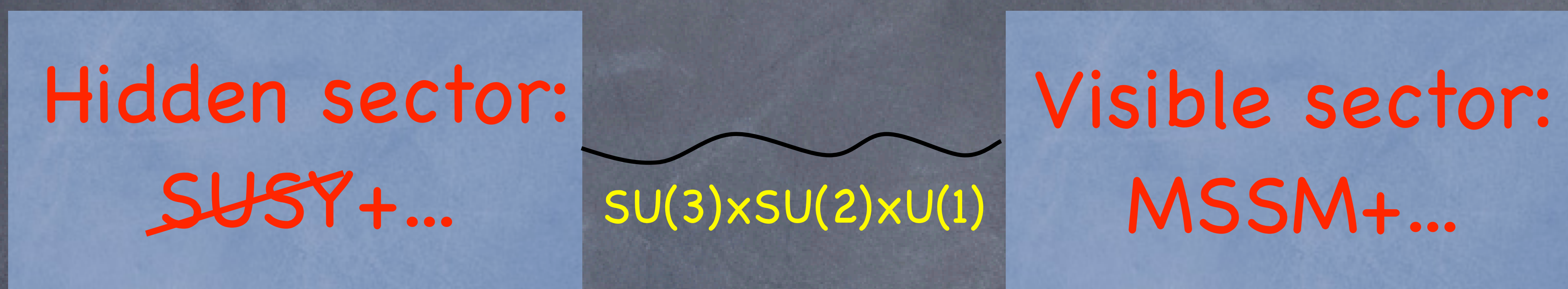
SUSY Flavor Problem

- There are strong experimental constraints on SUSY-breaking in the MSSM.
- The soft Lagrangian contains 100+ parameters in addition to the SM couplings. A generic point in this parameter space is experimentally ruled out:
  - Precision flavor-changing tests
  - Non-observation of superpartners





Mediation of ~~SUSY~~



- Ultimately, SUSY must be broken spontaneously in a separate hidden sector (Dimopoulos & Georgi).
- Constraints on the soft Lagrangian => constraints on how SUSY-breaking is ``mediated" from hidden sector to the MSSM.
- Gauge mediation is a calculable, viable framework that automatically solves the SUSY flavor problem.

Minimal gauge mediation

(Dine, Nelson, Nir, Shirman, ...)

$$\boxed{\begin{array}{c} W = \lambda X \phi^2 \\ \langle X \rangle = M + \theta^2 F \end{array}}$$

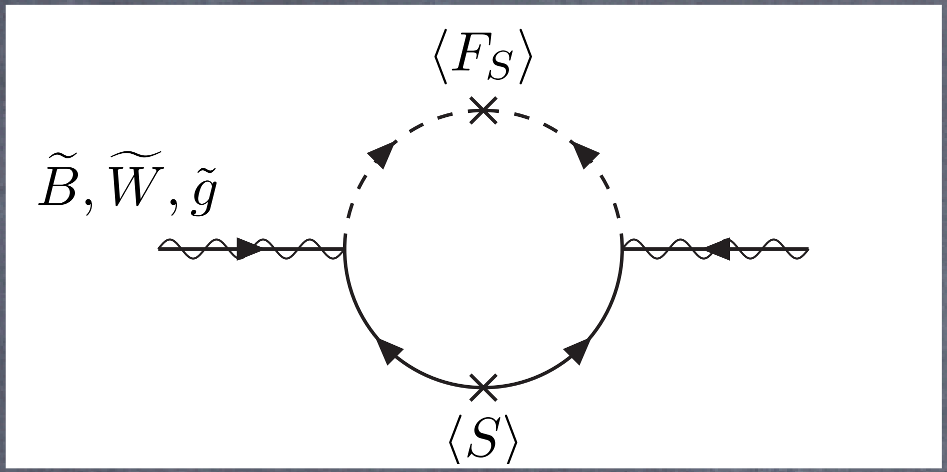
- X is a singlet spurion for hidden sector SUSY-breaking.
- ϕ are messengers in real representations of G_{SM}.
- Through their coupling to X, they receive tree-level SUSY-breaking mass splittings:

$$M_{\psi_\phi} = \begin{pmatrix} M & 0 \\ 0 & M \end{pmatrix}, \qquad M_\phi^2 = \begin{pmatrix} M^2 & F \\ F & M^2 \end{pmatrix} \quad \Rightarrow \quad M_\phi^2 = M^2 \pm F$$

- Loops of the messengers and SM gauge fields communicate SUSY-breaking to the MSSM.

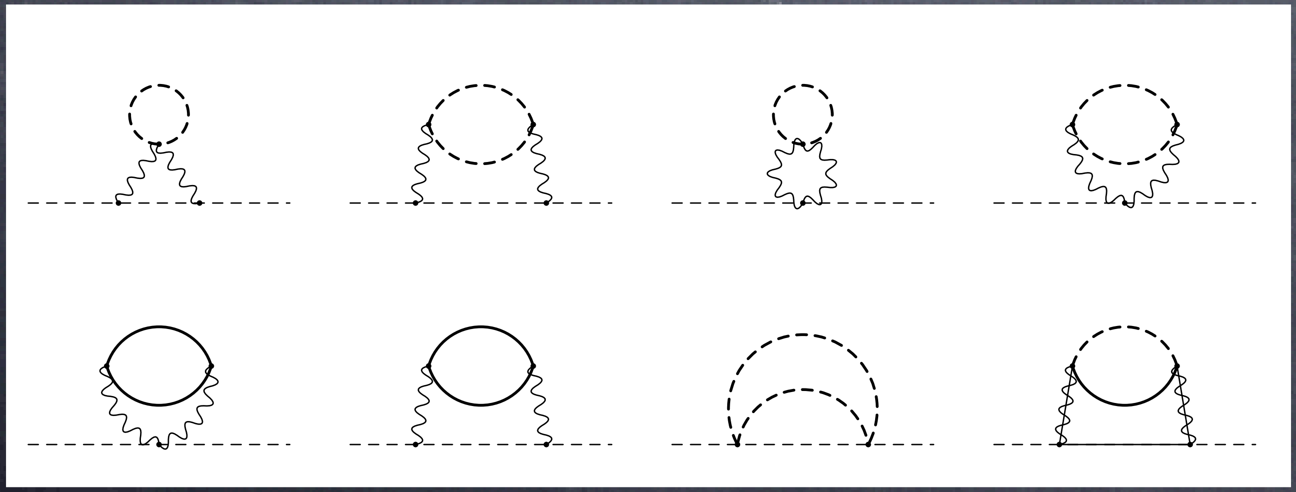
MGM Soft Masses

- 1-loop gaugino masses:



$$M_{r=1,2,3} \sim \frac{\alpha_r}{4\pi} \frac{F}{M}$$

- 2-loop sfermion mass-squareds:



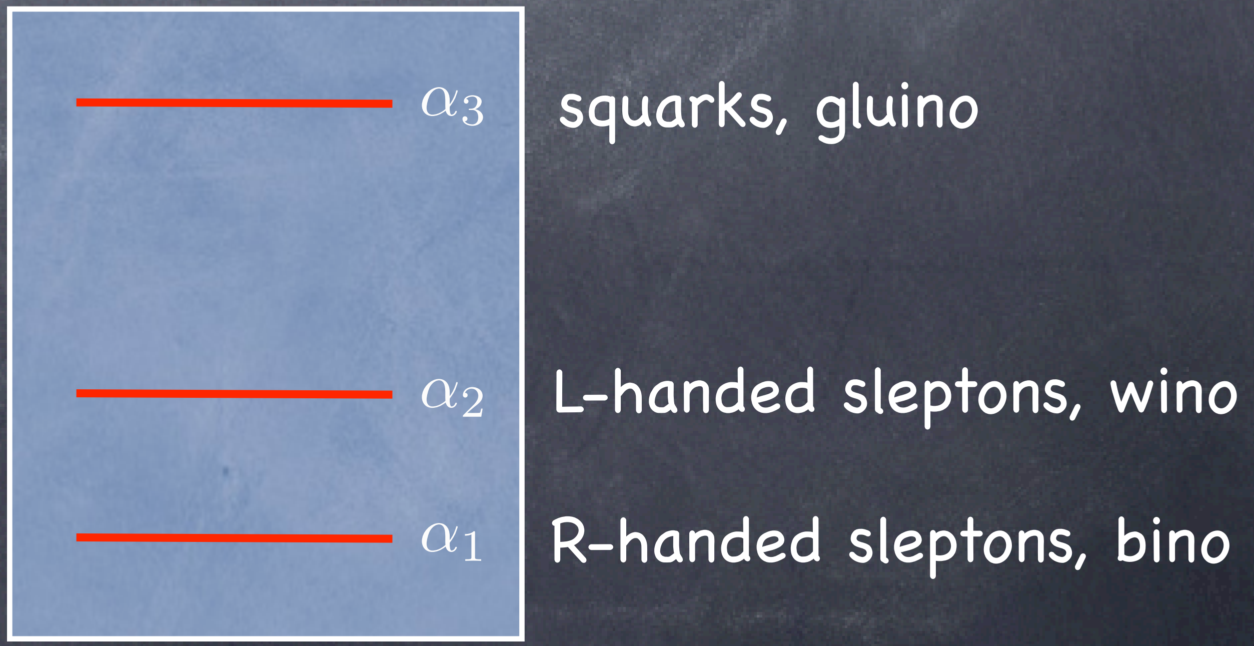
$$m^2_{\tilde{q}} \sim \left(\frac{\alpha_3}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2$$

$$m^2_{\tilde{\ell}} \sim \left(\frac{\alpha_{1,2}}{4\pi}\right)^2 \left(\frac{F}{M}\right)^2$$

MGM Phenomenology

$$M_r \propto \frac{F}{M}, \qquad m_{\tilde{f}}^2 \propto \left(\frac{F}{M}\right)^2$$

- MGM soft masses are controlled by essentially only one scale: F/M.
- This leads to many specific and well-known "predictions" of gauge mediation:
    - Gaugino unification
    - Sfermion mass hierarchy
    - Bino or slepton NLSP
    - ....



Beyond MGM

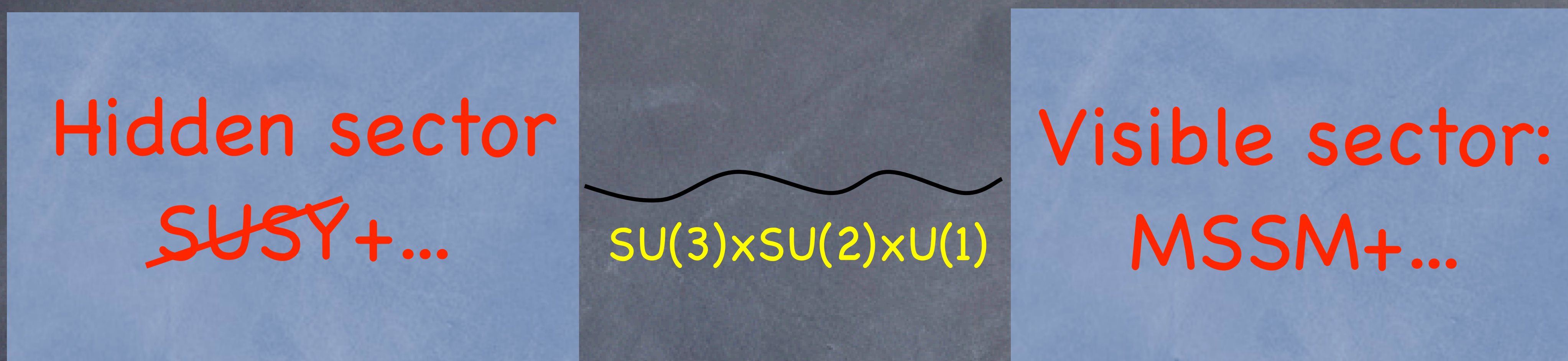
- To date, many models of gauge mediation have been constructed, with a wide variety of predictions.
- Questions:
  - What are the universal predictions of gauge mediation?
  - How large is the parameter space?
  - If we find hints of supersymmetry at the LHC, how can we tell whether it's gauge mediation?

Plan of the Talk

- ~~Background and Motivation~~
- General Gauge Mediation
  - Formulas for the soft masses
  - Sum rules
  - Parameter space
- General Messenger Gauge Mediation
  - Rewriting the soft masses
  - Superpotential vs. Kahler potential interactions
  - Simplifying limits
- Summary and Outlook

General Gauge Mediation

(Meade, Seiberg & DS)



- Hidden sector:
  - spontaneously breaks SUSY at a scale M
  - has a weakly-gauged global symmetry $G \supset G_{SM}$
  - includes messengers, if present
- Theory decouples into separate hidden and visible sectors in g->0 limit.
- Philosophy: work exactly in the hidden sector but to leading order in g.

Current Supermultiplet

- All the information we need about the hidden sector is encoded in the currents of G and their correlation functions.

- The current belongs to a supermultiplet:

$$j_\mu \to (J,\, j_\alpha,\, \bar{j}_{\dot\alpha},\, j_\mu)$$

(Assume G=U(1) for simplicity)

- In superspace, the SUSY generalization of current conservation is

$$D^2 \mathcal{J} = 0$$

$$\mathcal{J} = J + i\theta j - i\bar{\theta}\bar{j} - \bar{\theta}\sigma^\mu\theta j_\mu + \ldots$$

Current two-point functions

- By current conservation and Lorentz invariance, the nonzero two-point functions are:

$$\left.\begin{aligned}
\langle J(x) J(0)\rangle &\to C_0(x) \\
\langle j_\alpha(x) \bar{j}_{\dot\alpha}(0)\rangle &\to C_{1/2}(x) \\
\langle j_\mu(x) j_\nu(0)\rangle &\to C_1(x)
\end{aligned}\right\}\ \text{Real}$$

$$\langle j_\alpha(x) j_\beta(0)\rangle \to B(x) \qquad \text{Complex}$$

- If SUSY is unbroken, can show:

$$C_0 = C_{1/2} = C_1, \qquad B = 0$$

Coupling to visible sector

- Weakly gauge G=U(1):

$$\begin{aligned}\mathcal{L}_{int} &= g\int d^4\theta\,\mathcal{J}\mathcal{V} + \mathcal{O}(g^2)\\ &= g(JD + \lambda^\alpha j_\alpha + \bar\lambda_{\dot\alpha}\bar j^{\dot\alpha} + V^\mu j_\mu) + \mathcal{O}(g^2)\end{aligned}$$

- Integrate out hidden sector exactly. Effective theory for the gauge supermultiplet:

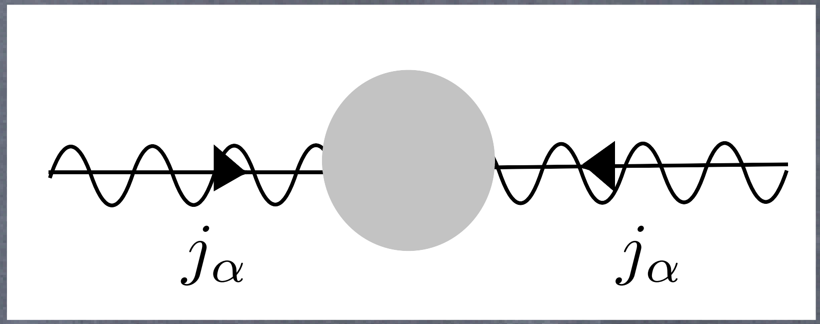
$$\begin{aligned}\delta\mathcal{L}_{eff} &= \frac{1}{2}g^2\tilde C_0(0)D^2 - g^2\tilde C_{1/2}(0)i\lambda\sigma^\mu\partial_\mu\bar\lambda - \frac{1}{4}g^2\tilde C_1(0)F_{\mu\nu}F^{\mu\nu}\\ &\quad -\frac{1}{2}g^2(M\tilde B(0)\lambda\lambda + c.c.) + \ldots\end{aligned}$$

- Soft terms can be written in terms of the current-current correlators.

Coupling to visible sector

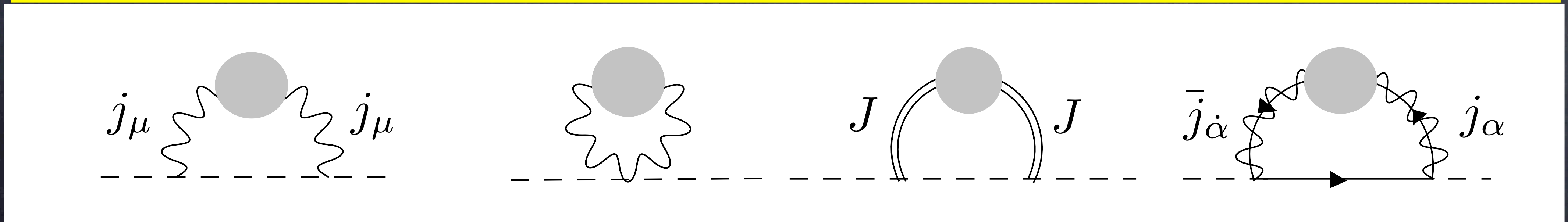
$$\delta\mathcal{L}_{eff} = \frac{1}{2}g^2\tilde{C}_0(0)D^2 - g^2\tilde{C}_{1/2}(0)i\lambda\sigma^\mu\partial_\mu\bar{\lambda} - \frac{1}{4}g^2\tilde{C}_1(0)F_{\mu\nu}F^{\mu\nu}$$
$$-\frac{1}{2}g^2(M\tilde{B}(0)\lambda\lambda + c.c.) + \dots$$

- Gaugino mass: $\boxed{M_\lambda = g^2 M\tilde{B}(0)}$



- Sfermion mass:

$$\boxed{\begin{aligned} &m_{\tilde{f}}^2 = g^4 A \\ &A = -\int \frac{d^2p}{(2\pi)^4}\left(3C_1(p^2/M^2) - 4C_{1/2}(p^2/M^2) + C_0(p^2/M^2)\right) \end{aligned}}$$



Generalizing to SU(3)xSU(2)xU(1)

- Trivial to generalize from U(1) to SU(3)xSU(2)xU(1)
- Each gauge group factor comes with a current supermultiplet

$$\mathcal{J} \to \mathcal{J}_{r=1,2,3}$$

- Gaugino and sfermion masses are given by the same formulas as before, convolved with group theory factors:

$$M_r = g_r^2 M B_r$$
$$m_{\tilde{f}}^2 = \sum_{r=1}^{3} C_{\tilde{f}}^r g_r^4 A_r$$

Quadratic Casmir

Sum Rules

$$m_{\tilde{f}}^2 = \sum_{r=1}^{3} C_{\tilde{f}}^r g_r^4 A_r$$

- Five MSSM sfermion masses f=Q,U,D,L,E are given in terms of 3 parameters $A_{r=1,2,3}$. So there must be 2 relations.
- These take the form:

$$\mathrm{Tr}\, Y m^2 = \mathrm{Tr}\,(B-L) m^2 = 0$$

- Sum rules true at the scale M. (Small) corrections from RG and EWSB.
- These relations were known before in specific different models (Martin & Ramond; Faraggi et al; Kawamura et al; Martin; Dimopoulos et al). Here we see they are completely general.

Parameter space

- The GGM parameter space consists of 9 real parameters:

$$A_{1,2,3}, \quad |B_{1,2,3}|, \quad \arg(B_{1,2,3})$$

- Comments:
  - SUSY CP problem in general
  - Gauge coupling unification not tied to gaugino unification
  - Parameter space much larger than minimal gauge mediation, where

$$B_r = \frac{F}{M}, \quad A_r = \left(\frac{F}{M}\right)^2$$

Parameter space

- Question: are there simple models of weakly coupled messengers that cover the entire parameter space?
- We are looking for an ``existence proof"
- Carpenter, Dine, Festuccia & Mason studied this question recently in the context of messenger models with small F-type SUSY breaking.
  (Cf. S. Martin, hep-ph/9608224.)
- They found models with the right number of parameters (6) but which did not cover the entire parameter space.

Parameter space

$$\mathcal{M}_{mess} = \begin{pmatrix} M^2 & F \\ F & M^2 \end{pmatrix} \to \begin{pmatrix} M^2 + D & F \\ F & M^2 - D \end{pmatrix}$$

- By considering messenger models with additional D-type splittings, one can cover the entire parameter space of GGM (Buican, Meade, Seiberg, DS).
- Such splittings could come from e.g. a U(1)′ with an effective FI parameter (Poppitz & Trivedi; Nakayama et al), or from hidden sector gauge dynamics as in "semi-direct gauge mediation" (Seiberg, Volansky & Wecht).
- The entire parameter space is physical and should be used as the basis for future phenomenological explorations of gauge mediation!

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- ~~Background and Motivation~~
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  - ~~Formulas for the soft masses~~
  - ~~Sum rules~~
  - ~~Parameter space~~
- General Messenger Gauge Mediation
  - Rewriting the soft masses
  - Superpotential vs. Kahler potential interactions
  - Simplifying limits
- Summary and Outlook

Messenger Models Revisited

- Parameter space of GGM is much larger than MGM -- more general, but less predictive.
- Most models of gauge mediation are messenger models. These tend to have fewer parameters and to be more predictive.
- How do we describe the most general messenger model in the GGM framework?

General Messenger Gauge Mediation

(Dumitrescu, Komargodski, Seiberg, DS)

~~SUSY~~ sector

$\mathcal{L}_{int}$

Messenger sector

SU(3)xSU(2)xU(1)

Visible sector

SM singlets
Scale: $\sqrt{F}$

Supersymmetric
SM charged fields
Scale: M

MSSM+...
Scale: M_{weak}

- SUSY-breaking and messenger sectors can be strongly coupled, but they are weakly coupled to one another.
- Recast everything in terms of operators and their correlation functions.
- This framework should include all messenger models...

General Messenger Gauge Mediation

- Most general interaction between messenger and SUSY-breaking sector:

$$\mathcal{L}_{int} = \frac{\lambda}{\Lambda^{\Delta_h+\Delta_m-3}} \int d^2\theta\, \mathcal{O}_h \mathcal{O}_m + \frac{\tilde{\lambda}}{\Lambda^{\tilde{\Delta}_h+\tilde{\Delta}_m-2}} \int d^4\theta\, \tilde{\mathcal{O}}_h \tilde{\mathcal{O}}_m + c.c.$$

- We would like to systematically expand in powers of the interactions and derive the leading-order soft masses in GMGM.

- For this it is useful to rewrite the GGM soft masses in a more convenient form...

Rewriting the soft masses

- Recall the chiral supermultiplet

$$\bar{D}\Phi = 0 \quad \Leftrightarrow \quad Q\phi = 0$$

- By analogy, an equivalent formulation of the current s'multiplet is to start with the defining relation:

$$D^2\mathcal{J} = \bar{D}^2\mathcal{J} = 0 \quad \Longleftrightarrow \quad Q^2 J = \bar{Q}^2 J = 0$$

- It follows that:

$$j_\alpha \equiv Q_\alpha J$$
$$\bar{j}_{\dot{\alpha}} \equiv \bar{Q}_{\dot{\alpha}} J$$
$$\sigma^\mu_{\alpha\dot{\alpha}} j_\mu \equiv [Q_\alpha, \bar{Q}_{\dot{\alpha}}] J$$

Rewriting the soft masses

Using action of supercharges, can show:

$$\begin{aligned} \langle Q^2 J(p) J(-p) \rangle &= \langle Q^\alpha J(p) Q_\alpha J(-p) \rangle \\ &= \langle j^\alpha(p) j_\alpha(-p) \rangle \\ &= M B(p) \end{aligned}$$

Similar manipulations lead to

$$\langle Q^2 \bar{Q}^2 J(p) J(-p) \rangle =$$
$$p^2 \Big(3C_1(p^2/M^2) - 4C_{1/2}(p^2/M^2) + C_0(p^2/M^2) \Big)$$

Rewriting the soft masses

- Thus:

$$\boxed{\begin{aligned} M_\lambda &= g^2 \langle Q^2 J(0) J(0) \rangle \\ m_{\tilde{f}}^2 &= g^4 \int \frac{dp^2}{p^2} \langle Q^2 \bar{Q}^2 J(p) J(-p) \rangle \end{aligned}}$$

(Buican, Meade, Seiberg, DS)

- Comments on the result:
  - Check: vanish when SUSY is unbroken.
  - At high momentum, only the JJ OPE matters. Can use this to prove convergence of the scalar mass integral.

Soft Masses in GMGM

$$M_\lambda = g^2 \langle Q^2 J(0) J(0) \rangle$$

$$m_{\tilde{f}}^2 = g^4 \int \frac{dp^2}{p^2} \langle Q^2 \bar{Q}^2 J(p) J(-p) \rangle$$

- Using rewritten GGM formulas, it is straightforward to work out leading-order GMGM soft masses for different types of interactions.
- Key simplifications arise from treating interactions perturbatively:
  - Correlators factorize into separate correlators in messenger sector and SUSY-breaking sector.
  - Messenger sector correlators are supersymmetric.

Kahler potential interactions

$$\mathcal{L}_{int} = \frac{\tilde{\lambda}}{\Lambda^{\tilde{\Delta}_h + \tilde{\Delta}_m - 2}} \int d^4\theta \, \tilde{\mathcal{O}}_h \tilde{\mathcal{O}}_m + c.c.$$

$$\langle Q^2 J(x) J(0) \rangle = \frac{\tilde{\lambda}}{\Lambda^{\tilde{\Delta}_h + \tilde{\Delta}_m - 2}} \langle Q^4 \tilde{\mathcal{O}}_h \rangle \int d^4y \, \left\langle \left(Q^2 \tilde{\mathcal{O}}_m(y) \right) J(x) J(0) \right\rangle$$

$$\langle Q^4 J(x) J(0) \rangle = \frac{\tilde{\lambda}}{\Lambda^{\tilde{\Delta}_h + \tilde{\Delta}_m - 2}} \langle Q^4 \tilde{\mathcal{O}}_h \rangle \int d^4y \, \left\langle \left(Q^4 \tilde{\mathcal{O}}_m(y) \right) J(x) J(0) \right\rangle$$

Comments:

- Gaugino masses can vanish at this order if messenger sector is R-symmetric.
- F-component of $\tilde{\mathcal{O}}_h$ does not contribute to gaugino masses. Seen previously in many examples...

Kahler potential interactions

$$\mathcal{L}_{int} = \frac{\tilde{\lambda}}{\Lambda^{\tilde{\Delta}_h + \tilde{\Delta}_m - 2}} \int d^4\theta \, \tilde{\mathcal{O}}_h \tilde{\mathcal{O}}_m + c.c.$$

$$\langle Q^2 J(x) J(0) \rangle = \frac{\tilde{\lambda}}{\Lambda^{\tilde{\Delta}_h + \tilde{\Delta}_m - 2}} \langle Q^4 \tilde{\mathcal{O}}_h \rangle \int d^4y \left\langle \left(Q^2 \tilde{\mathcal{O}}_m(y) \right) J(x) J(0) \right\rangle$$

$$\langle Q^4 J(x) J(0) \rangle = \frac{\tilde{\lambda}}{\Lambda^{\tilde{\Delta}_h + \tilde{\Delta}_m - 2}} \langle Q^4 \tilde{\mathcal{O}}_h \rangle \int d^4y \left\langle \left(Q^4 \tilde{\mathcal{O}}_m(y) \right) J(x) J(0) \right\rangle$$

Comments:

- $M_{\tilde{g}}^2 \sim \tilde{\lambda}^2 \ll m_{\tilde{f}}^2 \sim \tilde{\lambda}$. Scalars much heavier than gauginos. Split-SUSY phenomenology (Arkani-Hamed & Dimopoulos; Giudice & Romanino). Exacerbated little hierarchy problem.
- This setup includes semi-direct gauge mediation (Seiberg, Volansky & Wecht).

Superpotential interactions

$$\mathcal{L}_{int} = \frac{\lambda}{\Lambda^{\Delta_h+\Delta_m-3}} \int d^2\theta\, \mathcal{O}_h \mathcal{O}_m + c.c.$$

- Includes MGM, EOGM (Cheung, Fitzpatrick, DS), ...

$$\langle Q^2 J(x) J(0)\rangle = \frac{\lambda}{\Lambda^{\Delta_h+\Delta_m-3}} \langle Q^2 \mathcal{O}_h\rangle \int d^4y\, \langle Q^2(\mathcal{O}_m(y)) J(x) J(0)\rangle$$

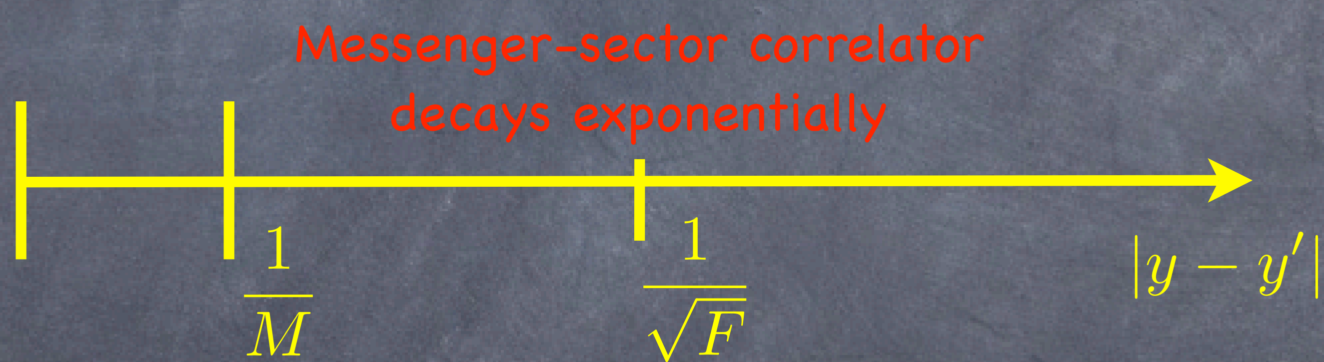
$$\langle Q^4 J(x) J(0)\rangle = \frac{\lambda^2}{\Lambda^{2(\Delta_h+\Delta_m-3)}} \int d^4y\, d^4y' \left\langle Q^4 \left(\mathcal{O}_h^\dagger(y)\mathcal{O}_h(y')\right)\right\rangle \times \left\langle Q^4 \left(\mathcal{O}_m^\dagger(y)\mathcal{O}_m(y')\right) J(x) J(0)\right\rangle$$

- Now sfermion and gaugino masses appear at the same order in the interaction -- a more natural spectrum.
- However, the sfermion masses are not completely factorized.

Simplifying limit

$$\langle Q^4 J(x)J(0)\rangle = \frac{\lambda^2}{\Lambda^{2(\Delta_h+\Delta_m-3)}}\int d^4y\, d^4y' \left\langle Q^4 \left(\mathcal{O}_h^\dagger(y)\mathcal{O}_h(y')\right)\right\rangle$$
$$\times \left\langle Q^4 \left(\mathcal{O}_m^\dagger(y)\mathcal{O}_m(y')\right) J(x)J(0)\right\rangle$$

- Factorization in a simplifying limit: $F \ll M^2$



- The SUSY-breaking sector correlator should be evaluated at short distance. So we can use the OPE:

$$\mathcal{O}_h^\dagger(y)\mathcal{O}_h(y') \sim \cdots + \frac{\mathcal{O}_\Delta}{(y-y')^{\Delta-2\Delta_h}} + \ldots$$
$$\langle Q^4 \mathcal{O}_\Delta\rangle \neq 0$$

Simplifying limits

$$\langle Q^4 J(x) J(0)\rangle = \frac{\lambda^2 \langle Q^4 \mathcal{O}_\Delta\rangle}{\Lambda^{2(\Delta_h+\Delta_m-3)}} \int d^4y\, d^4y' \, \frac{\langle Q^4 \left(\mathcal{O}^\dagger_m(y)\mathcal{O}_m(y')\right) J(x) J(0)\rangle}{(y-y')^{2\Delta_h-\Delta}}$$

$$\langle Q^2 J(x) J(0)\rangle = \frac{\lambda \langle Q^2 \mathcal{O}_h\rangle}{\Lambda^{\Delta_h+\Delta_m-3}} \int d^4y\, \langle Q^2(\mathcal{O}_m(y)) J(x) J(0)\rangle$$

- In this limit, ratio of sfermion to gaugino masses depends on Δ:

$$\frac{m^2_{\tilde{f}}}{M^2_{\tilde{g}}} \sim \left(\frac{\sqrt{F}}{M}\right)^{\Delta-2\Delta_h}$$

- We recognize the phenomenon of hidden-sector renormalization described in Cohen, Roy & Schmaltz!

Simplifying limit

$$\frac{m_{\tilde{f}}^2}{M_{\tilde{g}}^2} \sim \left(\frac{\sqrt{F}}{M}\right)^{\Delta - 2\Delta_h}$$

- If hidden sector is free @ messenger scale, then must have $\Delta \leq 2\Delta_h$ with equality only for elementary singlets. Then $m_{\tilde{f}}^2 \gg M_{\tilde{g}}^2$ or $m_{\tilde{f}}^2 \sim M_{\tilde{g}}^2$.
- If hidden sector is interacting CFT @ messenger scale, then Δ in principle unconstrained. If $\Delta > 2\Delta_h$, can get sfermions much lighter than gauginos.

This is the relevant regime for many interesting models: gaugino mediation, conformal sequestering, strong hidden sector solution to mu problem...

Summary

- We constructed a framework for analyzing general models of gauge mediation: arbitrary hidden sectors coupled to the MSSM via SM gauge interactions.

- Using our framework, we derived general properties of gauge mediation. These include:

  - Parameter space: 3 complex parameters (gaugino masses) and 3 real parameters (sfermion masses)

  - Two sum rules for sfermion masses

  - SUSY CP problem in general

- We constructed weakly-coupled messenger models which cover the entire GGM parameter space.

Summary

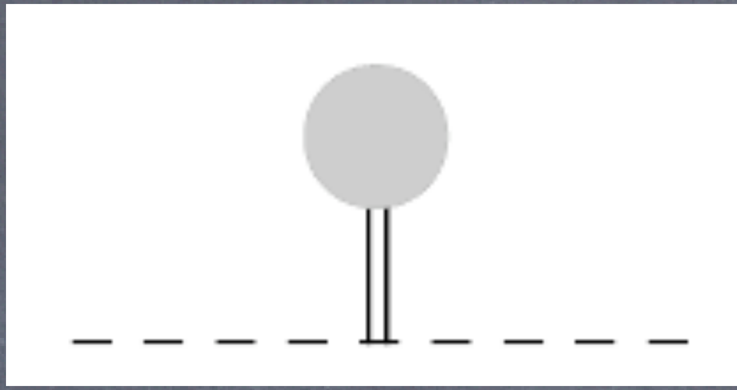
- We also built a framework within GGM to describe the most general messenger models of gauge mediation.
- We saw how the framework incorporated existing models and their phenomena.
- We also showed how the ratio of gaugino to sfermion masses depended on the type of interaction between messenger and SUSY-breaking sector, as well as the dynamics of these sectors.

Future Directions

- Detailed study of GGM at colliders. New, unexplored signatures at the Tevatron and the LHC! (Carpenter; Rajaraman et al.; Katz & Tweedie; Meade, Reece & DS; Kribs, Martin, Roy, Spannowsky)
- Is $\Delta > 2\Delta_h$ really possible in a SCFT? (Cf. Rattazzi, Rychkov, Tonni & Vichi; Hellerman)
- Extensions of GMGM framework to include mu/Bmu sector? (Cf. Komargodski & Seiberg)
- Can we prove positivity of sfermion masses in any context?

The End

Messenger Parity



- We have related the soft masses to the current two-point functions. However, we ignored the contribution of the hypercharge one-point function (FI parameter):

$$\langle J_1 \rangle = \zeta \neq 0$$

- It is dangerous because it contributes to the scalar masses:

$$\delta m^2_{\tilde{f}} = g_1^2 Y_f \zeta$$

- Not positive definite and lower order in g. So this can cause some scalars (esp. sleptons) to become tachyonic!

Messenger Parity

- Thus we would like the hidden sector to be invariant under a symmetry that forbids J one-point functions.
- The simplest such symmetry is a Z_2 parity:

$$\mathcal{J} \to -\mathcal{J}$$

- Examples of this symmetry in the context of minimal gauge mediation have been discussed in the literature. (Dine & Fischler; Dimopoulos & Giudice)